NASA TM-86328

NASA Technical Memorandum 86328

NASA-TM-86328 19850014574

Electrostatic Forming and Testing of Polymer Films on a 16-Foot Diameter Test Fixture

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February 1985

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N85-22885#

PREFACE

The Large Space Systems Technology Program was instrumental in investigating different forms of large, lightweight, deployable structures which could be carried on the Space Shuttle. Different forms and concepts of antennas as a type of large space system were investigated. One of the concepts chosen to be evaluated was the electrostatically controlled membrane reflector made of metallized material. The concept appears to be a good candidate for creating an antenna with high surface quality and has the ability to be packaged and deployed from the Shuttle with a significant reduction in weight compared to other antenna types.

Summary

The electrostatic forming of thin film membranes was proposed in 1978 by General Research Corporation (GRC) (ref. 1). A 16-foot diameter test fixture was designed and fabricated with a flat and curved back electrode. Several different types of polymer films were tested: Mylar (polyester), Kapton (polyimide), polyethylene, and Tedlar (PVF). It was shown with the flat back electrode that a membrane made with flat panels of film can be formed into a reflector shape with an F/D of 3.5 and a surface accuracy of approximately 1 mm. Also, it was shown with a curved back electrode that a preformed gored membrane can be formed into a reflector shape with an F/D of 1.0; however, the surface accuracy was approximately 11 mm, which was less than expected.

Introduction

The consideration of large antennas as large space structures started the search for an antenna type which would include the lightness of weight, compactness, and ability to be deployed that would be compatible with the Shuttle.

One of the candidates for evaluation was the electrostatic concept. For space applications, the concept was envisioned as two thin films supported by a lightweight deployable structure. One film would be attached to the structure and act as a back electrode while the second film or reflector would be separated from the back electrode and supported around the edges. The two membranes would be separated by a small gap which would permit the electrostatic charge to attract the reflector membrane toward the back electrode without touching. The force exerted by the electrostatic field would deflect the reflector membrane surface and create a reflector surface smooth enough to meet the antenna requirements.

The electrostatic ground testing was conducted in order to develop and understand the concept before progressing to a flight model test. The ground testing included several types of membrane material, two back electrode configurations, and several types of measurement systems.

Discussion

Test Fixture

The test fixture was fabricated from sections of 6-inch aluminum tubing which were welded together to produce a 12-sided support structure (fig. 1). In the original form, there was a 16-foot diameter tension ring over which the membrane was supported with the edges of the membrane being held by the clamping ring. Both the tension ring and the clamping ring could be adjusted to increase or decrease the tension in the membrane being measured.

The support structure was hinged to a base so that it could be rotated from a horizontal position to a vertical position. This permitted the test membranes to be installed and adjusted easily while in the horizontal position and then raised to the vertical position so that surface measurements could be made using the various devices described.

After the tests were completed with the flat back electrode, the support structure was modified to accommodate the flexible back electrode. This involved removing the tension and clamping rings and installing a series of 12 attachment brackets for the back electrode and a similar series of 12 attachment brackets for the reflector membrane. The 12 attachment brackets for the back electrode were attached to the Kevlar webbing which supported the flat panels of the back electrode and also provided an attachment point for the catenary cord which ran along the edge of the back electrode. The 12 attachment brackets for the reflector membrane attached to the membrane at the apex of the membrane gores.

Back Electrode Fabrication

The first flat back electrode was made up of a fiberglass coating over a lightweight foam center (fig. 2). The fiberglass surface was painted with conductive paint in a pattern of five concentric rings and each ring was connected to a separate power supply. Each ring was separated from the adjacent one by a 5/8-inch unpainted gap (fig. 3). At high voltage levels (>60 kV), it was observed that voltage feedover could be seen from a high voltage electrode to a lower one.

During the first series of tests, it was observed that the flat back electrode did not extend far enough toward the edge of the membrane. Due to the absence of the electrostatic force in this area, the membrane did not deflect properly around the edge. Also, the observed amount of voltage feedover and corona appeared excessive, so modifications were made to reduce these effects by lowering the conductivity of the surface and by increasing the gap between the electrode areas. Further, it was decided to increase the degree of controllability by increasing the number of control areas. As a result of these concerns, modifications were made to the original back electrode. The area of the back electrode was extended to cover more of the membrane area, the face of the back electrode was covered with 0.005-inch Mylar and the electrode control areas were painted on the Mylar surface using the same conductive paint with the separation between the control areas increased to 3 inches. The electrode pattern was changed to permit selective use of 3, 5, or 10 separate control areas (figs. 4, 5, and 6).

Since the basic flight concept of the electrostatically formed reflector would consist of two membranes; one to be the reflector and one to be the electrode, it was thought essential to test the flexible back electrode as a follow on to the flat back electrode. Consequently, the third back electrode test configuration was the flexible and curved back electrode which was intended to more closely simulate a back electrode as envisioned for a flight antenna. The back electrode was supported by a system of Kevlar webbing (fig. 7). The electrode surfaces were flat panels of 0.003-inch Mylar which made a faceted concave surface (ref. 2) with the individual electrode areas painted with the conductive paint used before (figs. 8, and 9). Ten control areas were connected to 10 power supplies and were separated by a 3-inch gap.

In order to get the Mylar panels to adhere to the Kevlar webbing, the webbing was "sized" with a thinned solution of adhesive. A good adhesive bond was secured, but it was observed later that voltage paths were created between electrode areas apparently because the adhesive was conductive. Also, in order for the conductive paint to adhere to the Mylar, the same sizing procedure was followed so that the normal non-conductance of the Mylar was affected to some degree such that voltage feedover was seen between adjacent control areas with only moderate voltage levels (35-40 kV). Consequently, the flexible back electrode did not give quite as satisfactory results as the earlier configurations (ref. 3).

High Voltage Power Supplies

During the initial testing, with the flat back electrodes, five power supplies were used to power the five separate control areas. The power supplies were capable of 0-80 kV at 0-1 ma. For the later testing, an additional five power supplies were secured in order that 10 control areas could be used. Special lightweight high voltage wire was used to connect the control areas to individual junction blocks where the lightweight wires were connected to the heavy, stiff, high-voltage cables from the power supplies. In order to complete the circuit, a ground wire was connected from the membrane to the ground side of the power supplies. Due to the high voltages that were involved, care was taken in fabricating the connectors and wire routing to minimize arcing and corona paths.

Materials

A variety of materials was considered for the reflector membrane initially, metallized cloth, metallized cloth mesh, metal mesh, and metallized plastic films. The space charging study (ref. 4) indicated that materials with openings such as woven cloth or woven meshes would not be suitable for electrostatically charged reflector surfaces in the space environment.

Several types of metallized plastic films were tested (Table 1). All of the materials were commercially available. The first one considered was Mylar (polyester film). The thinnest commercial grade in widths (56 inches) adaptable for 16-foot diameter reflectors was 0.0005-inch thick. The material was aluminized on both sides to <1 ohm/square (approx. 283 A).

Kapton (polyimide film) was also considered due to its superior strength and ultraviolet resistance qualities. It was available in 0.0003-inch thickness and was also aluminized to <1 ohm/square. Tedlar (polyvinylfluoride film) was another candidate material; 0.0005-inch material was aluminized on one side to <1 ohm/square. An 0.0005-inch aluminized polyethylene was also tried as a candidate material; however, it was the one which had the most undesirable characteristics due to its low strength and yield points.

Instron tests (ref. 5) were performed on the membrane materials to confirm the published strength data and to determine the stress which would be required to get the desired deflections. It should be noted that the tests on Kapton indicated that the material was stronger than the published Dupont data indicated (ref. 6). This required higher voltages in order to get the deflection desired.

Membrane Fabrication

For the initial testing (ref. 7) with the rigid flat back electrode, the membranes were fabricated from parallel panels of material which were joined by using a butt joint which was overlaid with a strip of thinner plastic film which was glued to the adjacent panels. The thinner plastic film was used to minimize the total thickness in the seam areas. The problems in fabricating the test membranes were primarily associated with the seam areas and developing fabrication techniques to get smooth seams across the whole (16 feet) test membrane. Some of the problems that were seen were:

(1) The seams were originally smoothed with a heated iron in order to speed up the curing of the adhesive; however, the heat application caused the thinner overlay material to shrink and cause wrinkling in the seam. This source of wrinkling was eliminated by not applying heat and allowing the adhesive to set at its normal rate;

(2) The two adjacent panels were positioned as smooth as possible next to each other and the film overlay was positioned over the joint as smooth as possible; however, the problem developed as each section was put into place and small wrinkles or puckers were seen at intervals which related to the length of each section as it was put into position. Efforts were made to correct this by laying the materials down with a minimum of tension so that the wrinkling effect was minimized;

(3) The commercial grade of material used frequently had surface markings which were apparently related to the rollers used in the manufacturing process. These markings or surface distortions were very noticeable and difficult to remove. No satisfactory method of removing these markings was developed; consequently, it was necessary to live with them during the test program. For a flight project, some method would have to be developed to insure the surface quality of the plastic material throughout the manufacturing process.

(4) It was suspected that the width of the panels as received from the vendor, might vary as to smoothness and straightness along the edges due to the manufacturing process. It was thought that this condition might influence the smoothness of the seams. A sample membrane was made from panels which had approximately 6 inches trimmed from each edge. This did produce seams that were better; however, this also resulted in more seams being required, which did not make for an overall smoother membrane.

(5) Difficulties were encountered in holding the adjacent panels smooth and flat while the seam overlay film was applied; double-backed tape was tried, a special silicon rubber work surface was tried, and an electrostatic surface was tried; however, the double-backed tape appeared to be the most practical compromise.

For the testing with the flexible-curved back electrode, a curved membrane made up of gored sections was designed. A template was developed for cutting out the individual gores and a curved form was made for supporting the gores while being glued. The gores were fabricated with attachment points at the apex of each two adjacent gores which were connected to catenary tapes running along the edge between the apex attachment points. One of the major problems of the gored membranes was the derivation of the gore shape to give a spherical reflector. Several methods (formulas) (Appendix 1) exist to derive mathematically correct gore shapes; however, when fabricated, the finished reflector shape appeared to be something less than a spherical shape.

The membrane made from 12 gores did not lay smooth and taut with the fixture in the horizontal position. The first effect seen was the excessive sag between attachment points of the individual gores. Pulling on the attachment points tended to remove some of the slack, but at the same time, caused the curvature of the gore (from the edge to the center) to change from its original spherical shape. The catenary was not effective in maintaining a relatively straight or taut edge to the gore in a plane parallel to the floor. As a cure to this slackness, a tapered slice (1/4-inch at edge, 0 in center) was removed from the edges of each gore. This appeared to have a small effect on the sag between attachments, but also affected the curvature of the dish so that it became more conical and less spherical. Another part of the same problem developed when the test fixture was raised to the vertical position, in that the looseness became more evident near the bottom edge of the membrane and created paths for arcing to develop, since the looseness of membrane material decreased the distance between the electrode and membrane. From this visual evaluation, it appeared that the spherical contour of the reflector was compromised when efforts to remove the edge looseness were attempted. Further efforts are needed to evaluate the fabrication of curved reflectors from basic flat material.

In discussions concerning the looseness seen on the width of gores used to develop a 12-gore reflector, comments and questions have been raised as to the need to increase the number of gores in order to cut down on the width of the individual gore. By increasing the gore number, this would effectively reduce the span of each straight gore panel making up the desired curved surface. Up to 84 gores have been used previously to fabricate spherical surfaces.

Measurement Techniques

Various measurement techniques were investigated and the most promising evaluated for use with the reflector surface types being considered for the membrane. The techniques under consideration were: (1) commercial distance measurement devices (infrared or laser beam reflectance ranging); (2) a LaRC designed and fabricated Laser Surface Sensor System; (3) a contracted photogrammetric measurement service of known high accuracy; and (4) a LaRC designed and implemented optical digital theodolite triangulation system.

At first, the simplest solution to accurate membrane surface measurement appeared to be commercially available beam reflectance ranging units, especially since the aluminized membrane material was itself reflective. However, initial testing of the devices with the aluminized membrane material revealed that the return beam was scattered to the extent that its amplitude was unusably small to the distance measuring receiver circuit. In order to concentrate the return beam, reflective tape, and small corner cube retro-reflectors were tested. The tape did not enhance the beam amplitude sufficiently. While the corner cube reflectors did provide a sufficiently concentrated return beam, the membrane material itself was so thin (0.0003 inches), it was readily apparent that attaching retro-reflectors to the surface would distort the membrane surface. Therefore, the use of this technique was discarded.

The second system evaluated was the Laser Surface Sensor System designed and fabricated at LaRC. This system is a modification of the Foucault Test Method described by Porter, Wright and Smith (refs. 8, 9, and 10) among others. The principle of operation is described as follows using figure 10. The laser and flat plate are located at the center of curvature of the reflector. If the surface is spherical, the reflected beam should return to its source regardless of where it strikes the reflector membrane. By measuring the amount of deviation in X and Y of the reflected beam from its source and using the deviations in a mathematical integration process, it is possible to determine the curvature of the surface. Several problems, however, were encountered in the practical application of this technique. First, the larger surface deviations, seams, and non-spherical areas caused large deviations in the reflected beam and the resulting discontinuities in the integration process made curvature measurement data unreliable. Second, the surface reflectivity affected the size and shape of the reflected laser spot necessitating estimation of spot center. This led to inaccuracies in the inputs to the integration process which at times caused distortion of the results.

Due to the practical problems associated with this technique, it was not considered further for test reflector measurement. It should be noted, however, that as a test reflector approaches a nearly spherical shape, the laser system should theoretically permit the reflector to be scanned and evaluated quickly.

A third technique used and evaluated was a photogrammetric measurement system supplied by an industrial photogrammetric consultant service (J. F. Kenefick, Inc.). The photogrammetric method used can be thought of as a complex triangulation problem. Referring to figure 11, targets or points of interest are placed on the surface to be measured. Single high resolution photographs are taken from multiple (in this case, three) locations so that the targets are imaged with widely divergent views (the camera axes are steeply inclined to each other). The photographic plates are checked for clarity on site and then taken to the vendor offices where measurements are made directly on the photographic plates with a very precise measuring device called a mono-comparator. These measurements are x, y photo-coordinates of the discrete target points. Angles to the target points are deduced from the photocoordinates and the previous laboratory measured focal length of the camera. The x, y, z coordinates are then calculated from the intersecting ray pairs from the different camera locations. The above calculations are actually done on a computer by the method of "least squares" with the results being available a few days later. True scale is accomplished by physical measurement of one or more target point pairs or another suitable photographed reference measurement. Average standard deviations were also computed (for each axis) and supplied along with departures from the "best fit" spherical membrane surface. The average standard deviations determined by this technique were 0.118 mm (0.00467") in the x and y directions and 0.342 mm (0.0135") in the z direction. This technique did provide a known high accuracy of the data (typically <1/2 mm). Its expense and minimum of several days turn-around time were not, however, conducive to the day-to-day high volume (many points, many times) measurements required. Therefore, except for specific "reference" occasions, this technique was reluctantly abandoned.

The fourth method evaluated and used for membrane surface measurement was an optical digital theodolite triangulation system. Figure 12 shows the system setup. Two K&E Vectron digital theodolites with an angular resolution of 0.001 grad (3.24 sec.) are shown with an HP-85 desktop computer. A measurement system was established based on the triangulation between the two theodolites and the points to be measured. The two theodolites were approximately 21 feet from the test reflector membrane and approximately 18 feet from each other. These numbers, although not rigorously optimized, were very close to the best achievable under the test conditions. The distance of the theodolites from the test fixture (a 16-foot diameter upright ring with the bottom of the ring approximately 1 foot above floor level) was a compromise between getting as close as possible to the test fixture for theodolite pointing accuracy while still being able to have a reasonable viewing angle for test points located at the top (approximately 17 feet above floor level) of the test fixture. The distance between the two theodolites was limited by the physical width of the test facility (maximum accuracy would have been attained at approximately 42 feet theodolite separation). In order not to induce errors by physically measuring the distance between the theodolites, a basic measurement reference length (a surveyor's tape) was introduced into the theodolite's field of view so that these data could be directly input into the triangulation calculations. A benchmark reference point was also secured to the structure of the test facility to reference the angle data taken and to provide repeatability (by frequent checking) of this data. Along with standard error minimization techniques such as taking the average of direct and reverse readings of each point, a number of steps were initiated to minimize the errors generally seen in attempting very high accuracy measurements. These included: using heavyweight instrument stands with all adjustments securely locked, special securing (much tighter than normal) of the theodolites to the instrument stands to assure no unintentional movement, securing and special potting of the stands to the facility floor to assure and verify that no movement takes place, and the use of special target alignment rings when determining the theodolites' baseline readings. Special theodolite operator operational and accuracy techniques were also developed to assure accuracy and repeatability.

Measurement System Analysis

The derivation of the triangulation method can be explained by referring to figure 13. The x, y, z coordinates of a point, P, are needed with theodolites located at points O and A. Assuming a value for distance OA, these are easily calculated as follows:

$$\angle ORA = 180° - \angle ROA - \angle RAO$$

$$OR = \sin \angle OAR \left(\frac{OA}{\sin \angle ORA} \right)$$

$$x_p = Oh = OR \cos \angle ROA$$

$$y_p = Rh = OR \sin \angle ROA$$

$$z_p = PR = OR \tan \angle POR$$

Simplification of the theodolite setup can be achieved by noting that neither $\angle PAR$ nor $\angle PA^1R^1$ is used in the above calculations. Therefore, the elevation (or z coordinate) of the theodolite at point A along the z axis is not required to be the same or even close to the elevation of the theodolite at point O along the z axis. In fact, elevation readings from the theodolite at point A are not used at all!

Since OA was assumed, the solution for points x_p, y_p, z_p is scaled to that assumed value. True scale, however, can be easily obtained, by first calculating the end points of a known reference length (a surveyor's tape). The scaled distance, d, between the two points is determined by:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

Dividing the known distance on the surveyor's tape by the scaled distance calculated gives a scale factor which, when multiplied by any scaled dimension results in true scale for that dimension.

A measurement of the curvature of the test membrane was required. It was decided to measure a number of points on the ring of the test fixture, select the three most in planarity with the test fixture ring, and then from analytic geometry (ref. 11), mathematically define a plane through these three points. Once this plane is analytically defined, the distance from any (x, y, z) point in space to this plane can be calculated (ref. 11). By simply measuring a number of points across (or enough points to define) the test membrane, its curvature can be defined with respect to the three-point reference plane. Repeatability of data taken in this manner was verified on many occasions by using benchmark reference targets attached to the facility structure. Repeatability of ±1 mm was consistently achieved.

Another method of measuring the curvature of the test membrane was also used. Points measured (x, y, z coordinates) on the nearly spherical test membrane surface were used to determine the best fit spherical surface by the method of least squares. The radius vector from the center of this sphere to each point was calculated and compared to the best fit radius to give individual departures. This technique was used primarily for comparisons on occasions when "reference" photogrammetric data were available. Comparison of theodolite data with "reference" photogrammetric data was consistently accurate to within ±1 mm.

To enhance the theodolite measurement system, a third theodolite was secured and incorporated into the system. It was believed, at the time, that with three units, the accuracy of the measurements could be improved, the speed of the measurements could be improved, the speed of the measurement operation could be increased, and the operation of the system simplified. Practically, it was learned that three units did not improve the system since the room dimensions did not permit the units to be placed at the most advantageous locations, also, the third unit did not improve the speed of the operation or simplify the operation.

A comparison of the accuracy of the last three methods (laser, photogrammetric, and theodolite) can be made. The least accurate (and unfortunately unusable in our case) was the laser system. This was due to its inability to handle the larger surface deviations, seams, and other nonspherical areas. The most accurate technique used was photogrammetry. Its standard deviation averaged better then 0.13 mm (0.005 inch) in the x and y directions and better than 0.4 mm (0.015) inch in the z (depth) direction. The second most accurate technique was the theodolite triangulation system. Repeatability to fixed benchmarks and agreement by comparison to the photogrammetric system was consistently within ±1 mm (0.039 inch).

Each of the three systems, however, had unique characteristics which should be noted and are as follows: (1) in the laser system, a quick analysis of a nearly spherical surface might be achieved although we did not verify this; (2) the photogrammetric technique, besides being the most accurate, allowed the data to be "frozen" in time and preserved for future additional analysis; however, the data analysis time was relatively lengthy--on the order of several days minimum after the photographs were taken; the costs and setup of this system were not insignificant either; and (3) the theodolite system gave accurate readings, but the process of taking the angle readings of each point was time consuming (a maximum of around 40 points per hour <u>not</u> including setup time). This became a problem at times, such as when the hygroscopic changes in the Kapton film caused dimensional changes over a several-hour period. In the end, the flexibility (variable target placement and number of targets plus the ability to restart the measurements) of the theodolite system for day to day use, along with its high accuracy, made it the system of choice on most occasions.

Space Charging Analysis

During initial consideration of potential membrane candidates, metallized mesh was thought to have characteristics which would make it attractive for use on the electrostatically formed antenna. It was thought that the mesh would be stronger, easier to form, and easier to work with than the lightweight plastic films also being considererd.

Several meshes were considered: gold plated, molybdenum wire woven in a tricot type mesh where the weave was significantly stiffer in one direction (warp) than the other (woof), copper plated dacron woven mesh, and silver plated dacron mesh.

Comments made by LeRC personnel about the space charging problems they had encountered led to a study being done on the space charging effects which would be predicted for an electrostatically charged mesh or film antenna surface. The study was made by Systems, Science and Software, Inc. (S^3) (ref. 4) under LeRC direction.

Conclusions reached in the study were:

(a) The electrostatically controlled membrane reflector is a viable concept for space applications. However, great care must be taken to enclose the high-voltage electrodes in a Faraday Cage structure to separate the high-voltage region from the ambient plasma.

(b) Conventional spacecraft charging such as that seen at GEO should not be a problem provided auxiliary structures (such as booms) are given non-negligible conductivity and adequate grounding. However, at LEO the plasma is colder and denser and has a greater potential for causing problems to high-voltage systems.

(c) Ram ions exist at LEO which, may in some instances, cause sputtering of external surfaces by atomic oxygen and degradation of aluminized surfaces within a time period of days or months.

(d) Plasma entering the high-field region of the antenna constitutes a parasitic current and, when multiplied by the applied voltage, a power loss. Plasma or electrons can enter the high-field region through holes or gaps in the "Faraday cage," through the holes in the weave of metallized cloth, or by penetration of a thin plastic membrane. At LEO, it is estimated that an opening in the Faraday cage of approx. 1 meter^2 in a covering of 10^4 meters^2

is likely to produce an intolerable power loss. Calculations have shown that a substantial fraction of electrons incident on a metallized cloth will appear as parasitic current and will cause an intolerable power drain of several kilowatts. This would rule out use of metallized cloth in an electrostatically formed reflector. Penetration of thin plastic membranes would be more of a problem at GEO (with an estimated maximum power loss of 100 watts) than at LEO with the LEO power loss estimated to be at most, a few watts.

Membrane Coating Analysis

Kapton (polyimide) film has a hygroscopic coefficient of expansion of 2.2×10^{-5}in/in/percent R.H. and thermal coefficient of expansion of 2.0×10^{-5}in/in/°C. During the summer when humidity and temperature were relatively high, it was observed that the temperature could change approximately 3° to 4° during the testing and the humidity would change approximately 2 to 3 percent during the same time. Even though the changes were small, the size of the test membrane (16-foot diameter) was such that the dimensional change in the depth of the reflector was approximately 0.3-inch over a 3 to 4 hour test period. Acrylic resin coatings were available which could seal the Kapton and prevent the absorption of water. A small test program was set up to evaluate the effectiveness of the coating. Samples of plain clear Kapton, acrylic resin coated Kapton and aluminized Kapton were subjected to the same humidity conditions and the weights of the various samples were compared with the original dry weights of the samples. The results showed that the coating did not appear to be significantly better than the samples which had been aluminized. Consequently, the results were compared and the coating was not used (fig. 14).

Concluding Remarks

1. Electrostatic forming of reflector surfaces can be done. However, it was not demonstrated that F/D=1 reflectors could be made as smooth as F/D=3.5 reflectors because the same level of tension could not be reached.
2. Much more work needs to be done in developing practical ways of fabricating gored reflectors that meet the contour and dimensional requirements of F/D=1 reflectors.
3. Measurement of the reflector surface can be done effectively by both the theodolite and photogrammetric methods.

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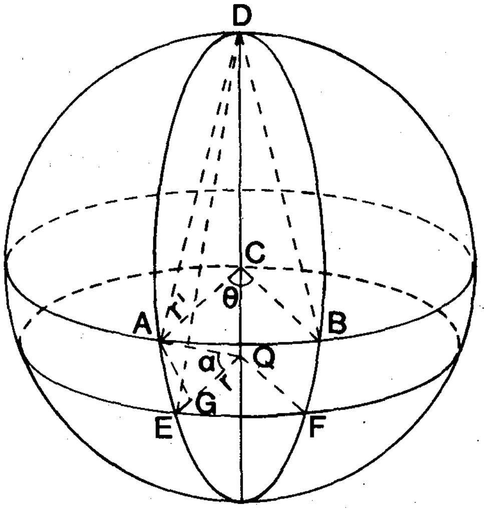
APPENDIX 1

Gore Pattern Formulas

1. Computer Program: "GOREE"



where:

$\widehat{EF} = r\theta(\angle ACB = \theta)$

$r = QE = QF = AQ$

$\widehat{AE} = 10$ inches

$\angle AQE = \alpha$

$\widehat{AE} = r\alpha$

$\alpha = \frac{\widehat{AE}}{r}$ (radians)

$\cos\alpha = \frac{QG}{AQ} = \frac{QG}{r}$

$AC = QG = r\cos\alpha = r'$

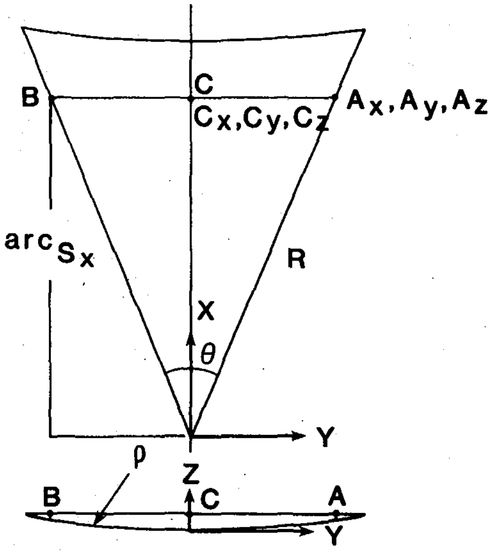
$AC = r'$

$S' = \widehat{AB} = r'\theta = (r\cos\alpha)(\theta)$

$S' = r\left(\cos\left(\frac{\widehat{AE}}{r}\right)\right)(\theta)$

$$\text{ORDINATE FROM CENTER LINE} = \frac{S'}{2} = \frac{\frac{r\theta\pi}{180}\left(\cos\left(\frac{\widehat{AE}}{r} \times \frac{180}{\pi}\right)\right)}{2}$$

2. Computer Program: "MIGOR 1"



$\ell_{oc} = f(x)dx$

where:

$f = \sqrt{\frac{1 - ax^2}{1 - bx^2}}$

$a = b(1 - t)$

$b = t/p^2$

$t = 1 + \tan^2\theta/2$

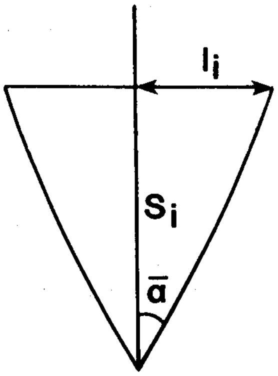
$A_z = \rho - \sqrt{\rho^2 - R^2}$

$A_y = C_x \tan\theta/2$

$\theta = 2\tan^{-1}(A_z/R)$

ρ = radius of curvature

3. Computer Program: "MIGOR 2"



$$\ell_i = \rho \sin\bar{\alpha} \sin\left(\frac{S_i}{\rho\cos\bar{\alpha}}\right)$$

where: ℓ_i = half gore width
S_i = center arc length
ρ = radius of curvature

These three methods produce gore patterns which are slightly different. These small differences were the source of problems in the fabrication of the test membranes. A sample membrane made to the Migor 2 coordinates appeared very loose after installation, a sample made to the Goree coordinates appeared slightly loose. By trimming a triangular slice from each panel, a membrane was fabricated which appeared to be nearly satisfactory. However, with the test fixture in the horizontal position, there was a sag in the catenary between attachment points normal to the plane of the catenary. Attempts to remove the sag by tightening the attachment points caused the curvature of the reflector to change. This sag was never completely removed.

Materials

Name	Thickness (inches)	Aluminized	Aluminum Thickness	Reference Tensile Modules	Hygroscopic Coefficient Expansion	Thermal Coefficient Expansion
Mylar (Polyester)	0.0005	2 sides	1 ohm/square	550,000 psi	0.6 x 10^{-5}in/in/%RH	1.7 x 10^{-5}in/in/°C
Kapton (Polyimide)	0.0003	1 side & 2 sides	1 ohm/square	430,000*	2.2 x 10^{-5}	2.0 x 10^{-5}
Tedlar (Polyvinylflouride)	0.0005	1 side	1 ohm/square	323,000	est. 0.38 x 10^{-5}	2.8 x 10^{-5}
Polyethylene	0.0005	1 side	1 ohm/square	10-40 x 10^3	est. 1.13 x 10^{-5}	10-20 x 10^{-5}

*Instron test results show tensile modules of 655,000 psi.

Table 1.

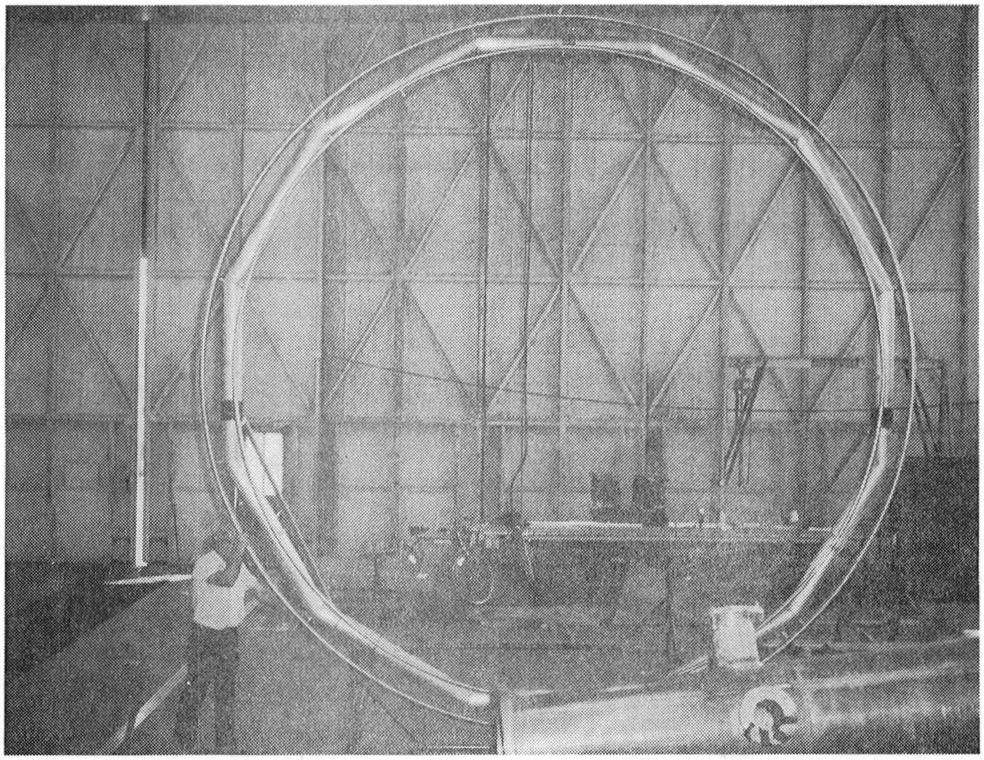


Figure 1. 16-Foot Diameter Electrostatic Test Fixture.

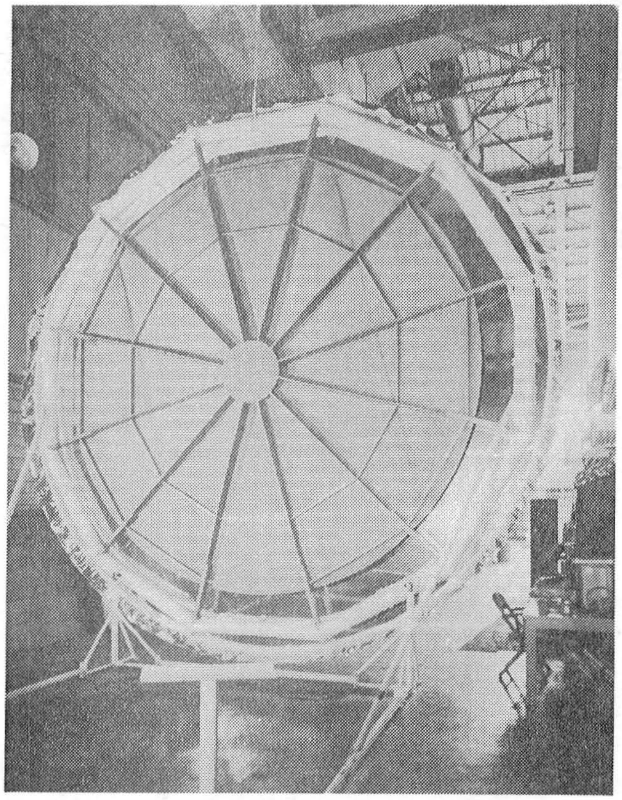


Figure 2. 16-Foot Diameter Test Fixture with Flat Back Electrode Installed (Back View).

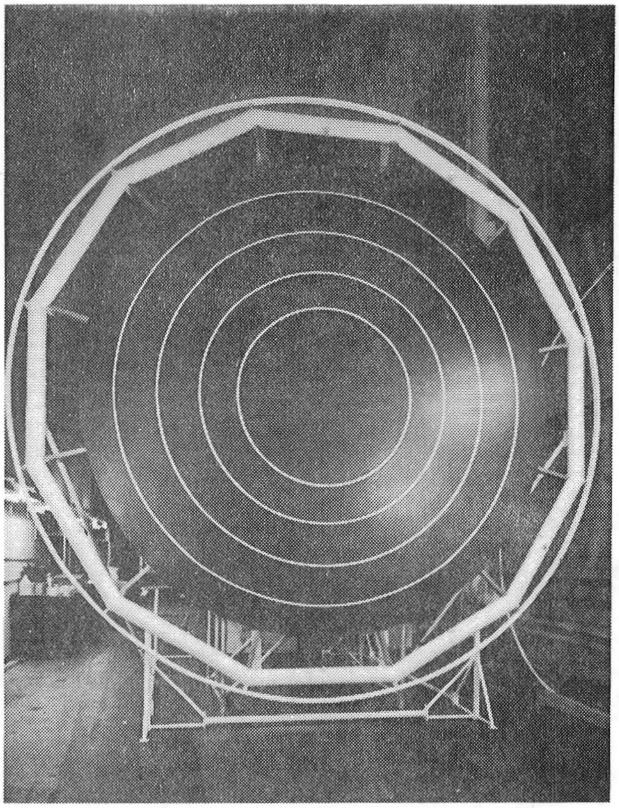


Figure 3. 16-Foot Diameter Test Fixture with Flat Back Electrode Installed (Front View Showing 5 Electrode Areas).

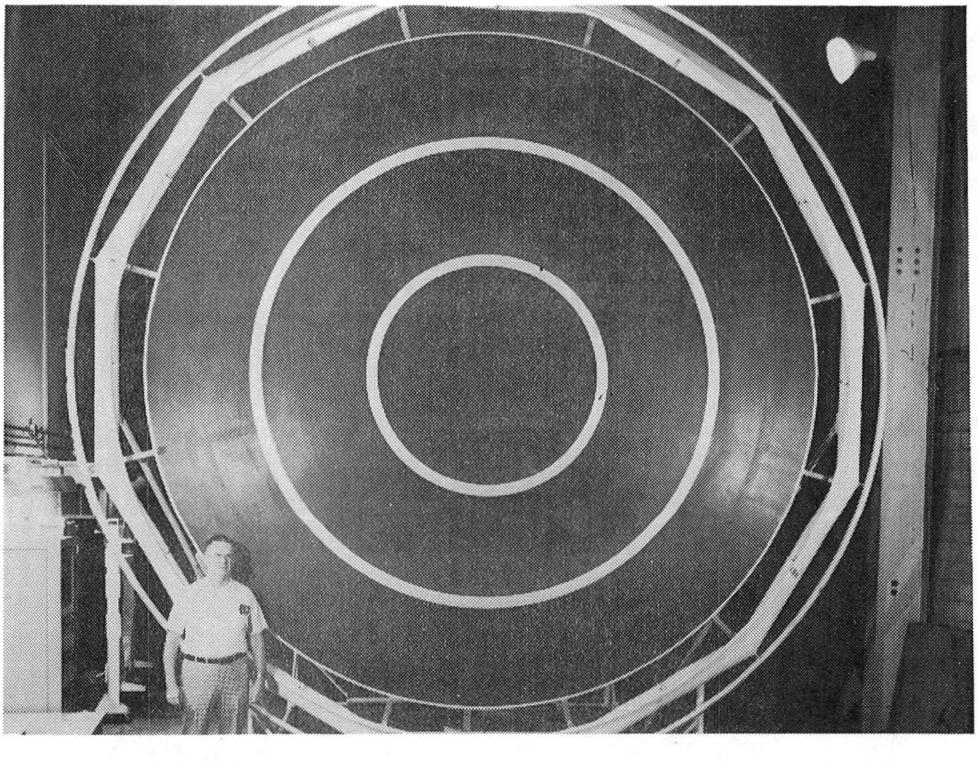


Figure 4. 16-Foot Diameter Test Fixture with Modified Flat Back Electrode (Front View Showing 3 Electrode Areas).

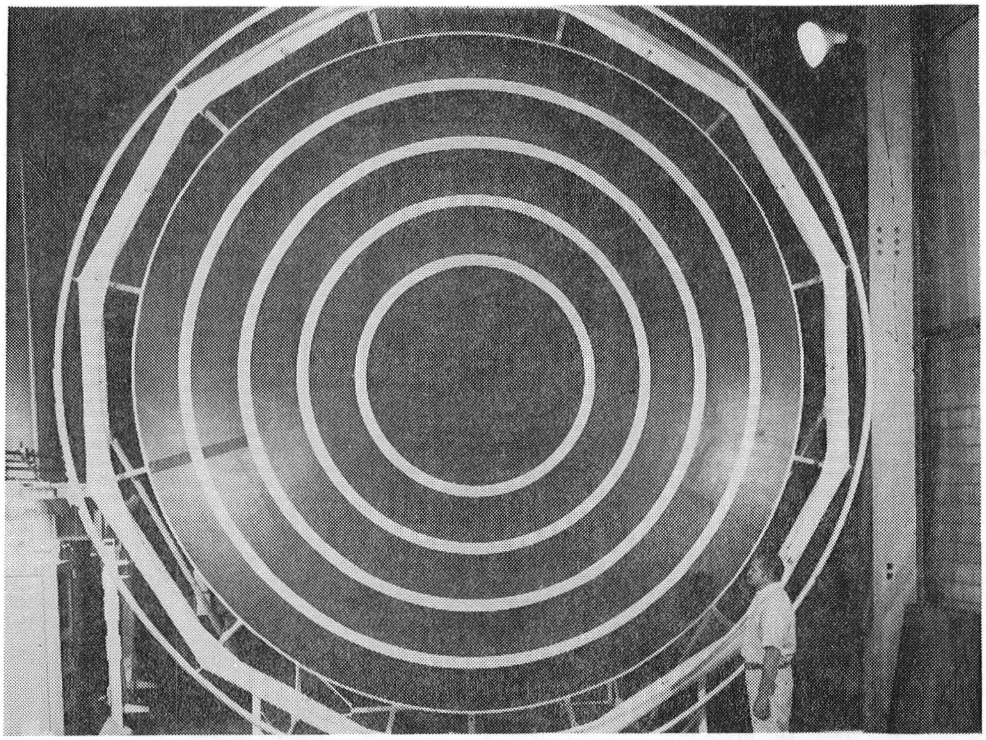


Figure 5. 16-Foot Diameter Test Fixture with Modified Flat Back Electrode (Front View Showing 5 Electrode Areas).

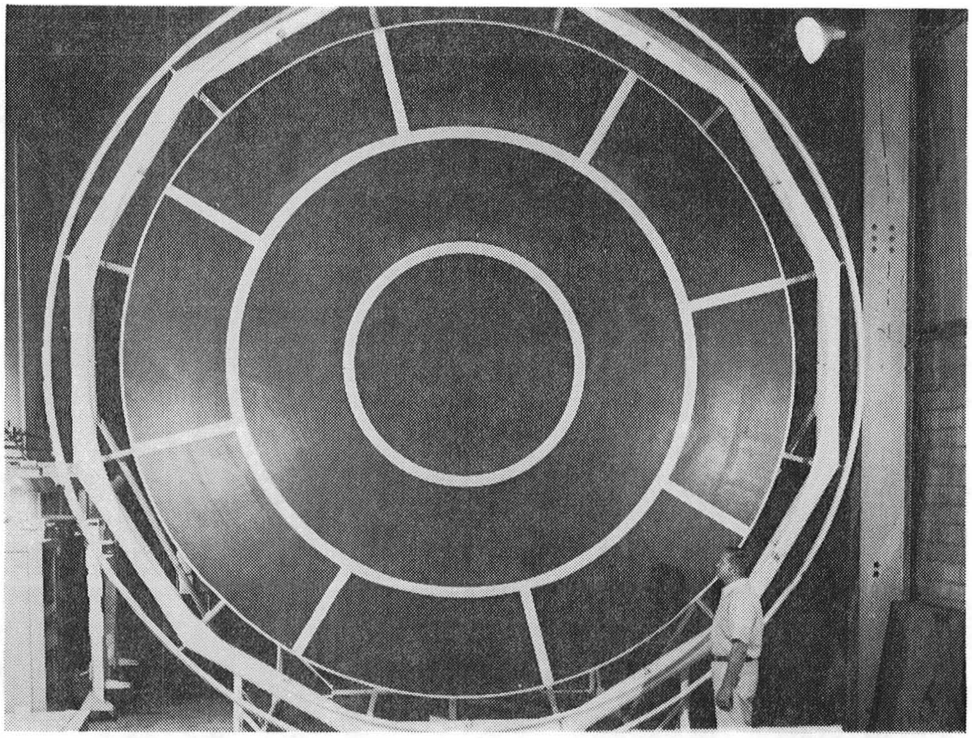


Figure 6. 16-Foot Diameter Test Fixture with Modified Flat Back Electrode (Front View Showing 10 Electrode Areas).

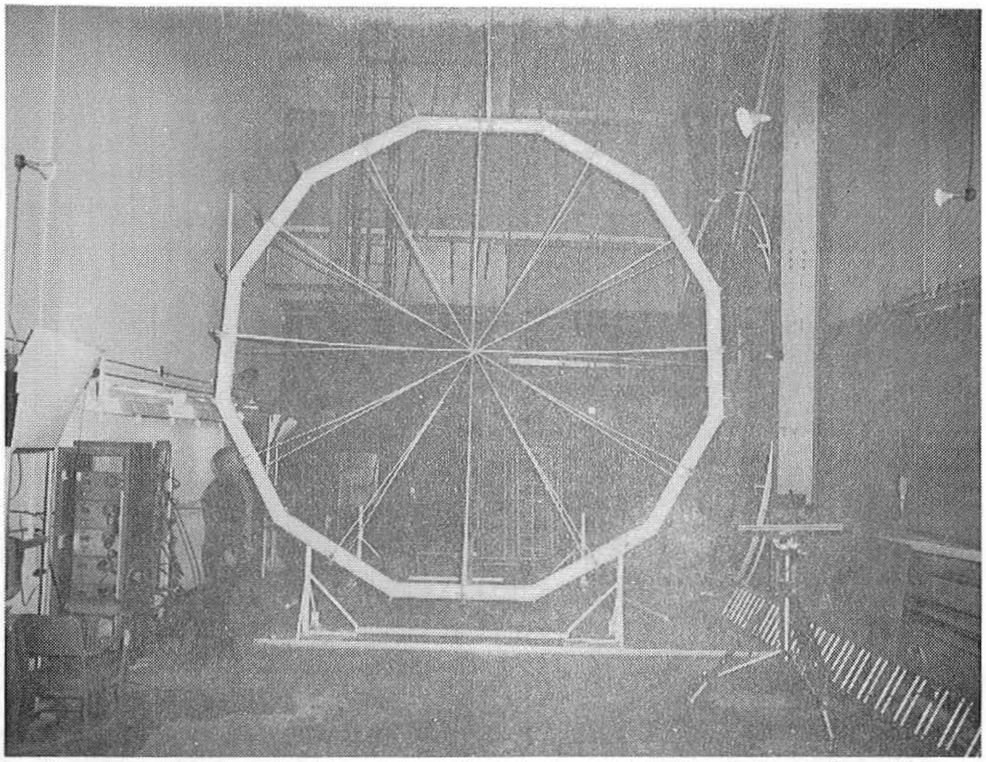


Figure 7. 16-Foot Diameter Test Fixture with Kevlar Support Tapes for Flexible Back Electrode.

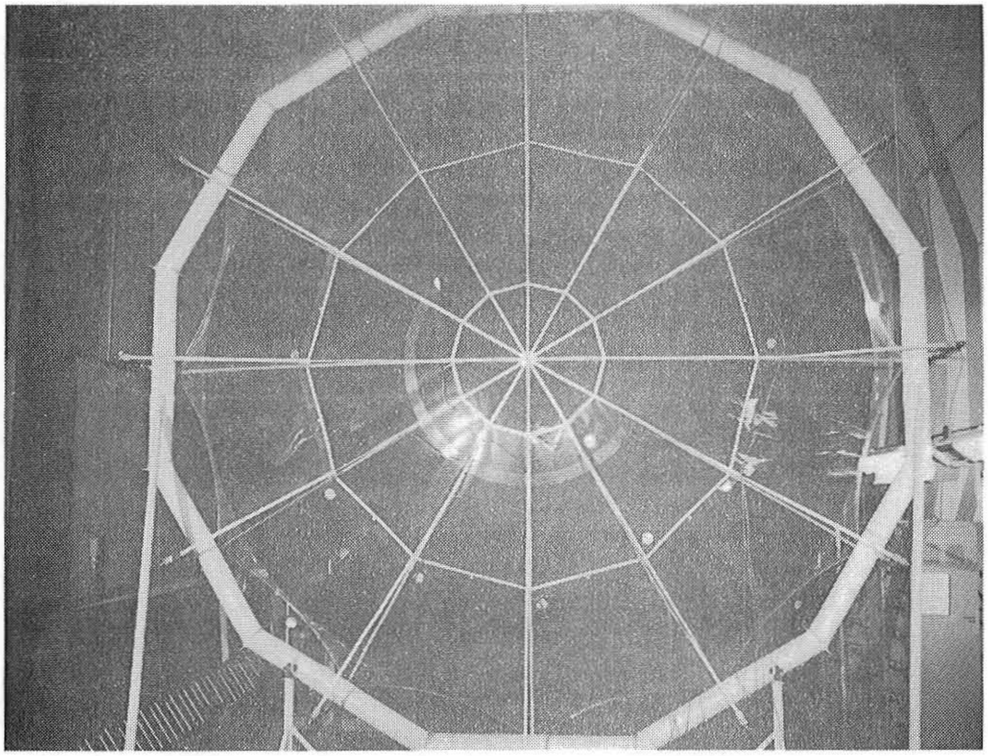


Figure 8. 16-Foot Diameter Test Fixture with Flexible Back Electrode Installed (Back View Showing Kevlar Support Tapes and Electrode Cables).

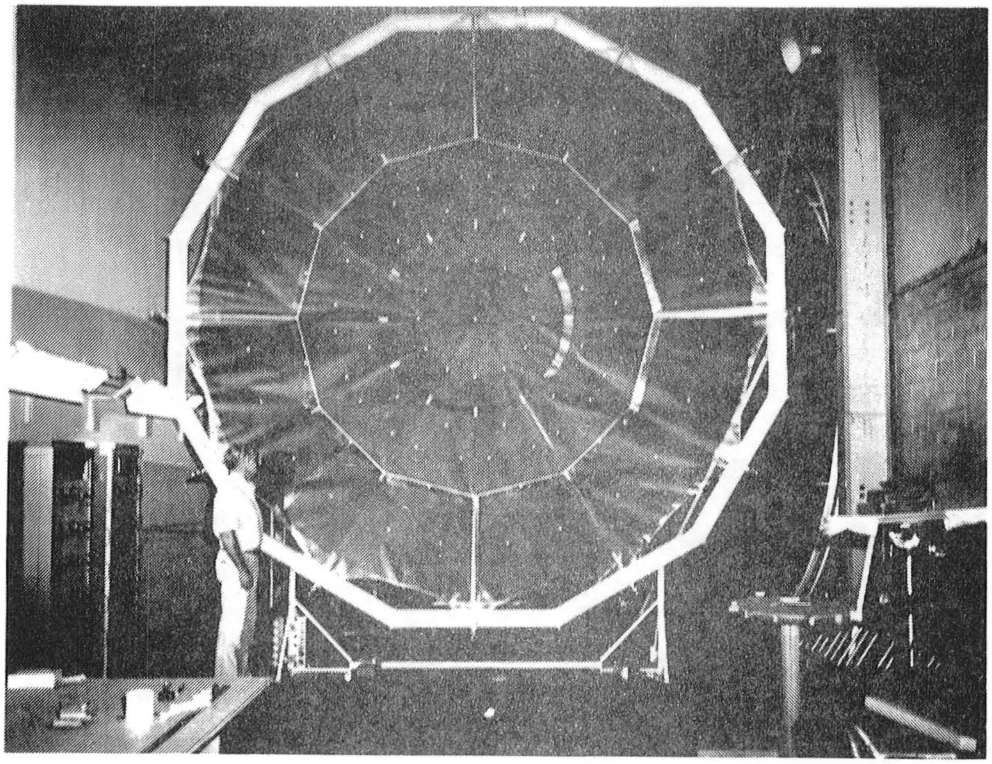
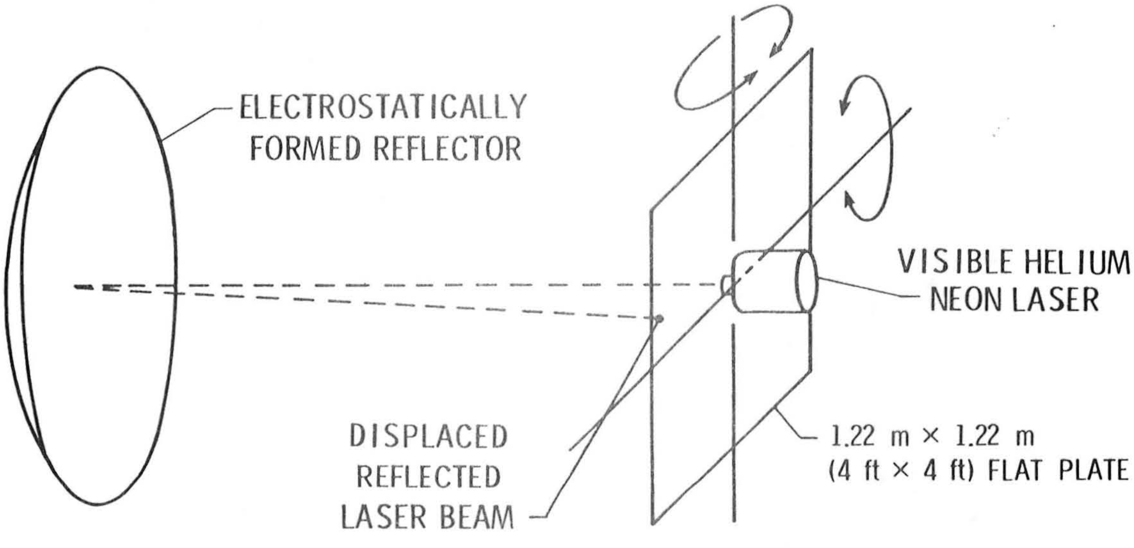


Figure 9. 16-Foot Diameter Test Fixture with Flexible Back Electrode Installed (Front View Showing 10 Electrode Areas with Measurement Points).



MEASUREMENT OF DISPLACEMENT OF REFLECTED BEAM PRODUCES CONTOUR OF SURFACE IN VERTICAL AND HORIZONTAL PLANES

Figure 10. Schematic of Laser Measurement System.

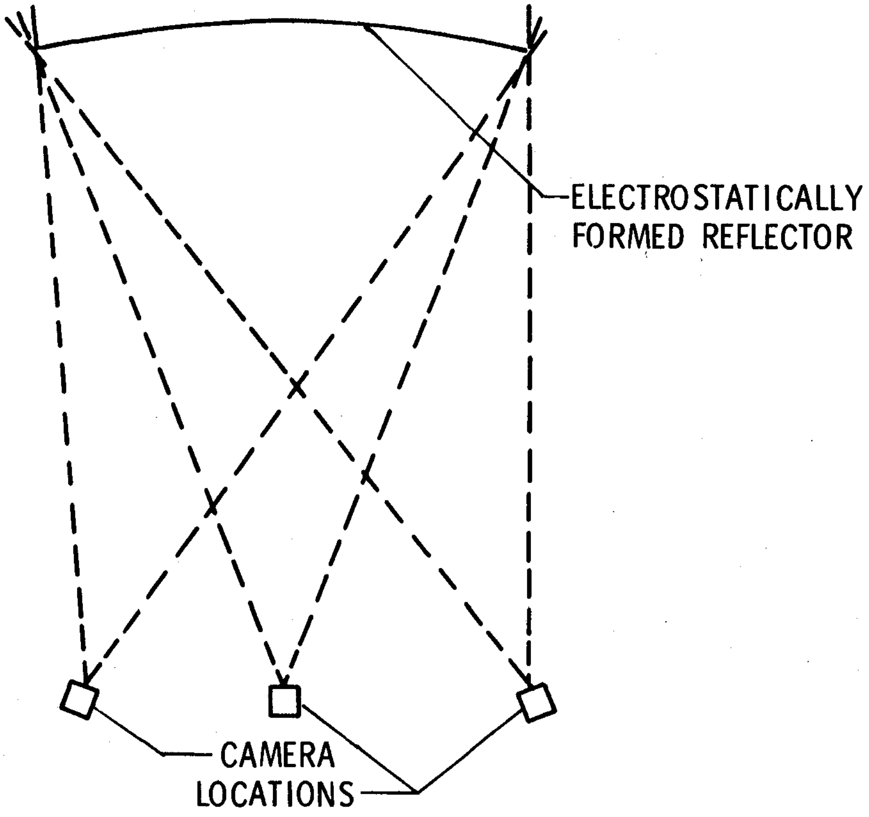


Figure 11. Schematic of Photogrammetric Measurement System.

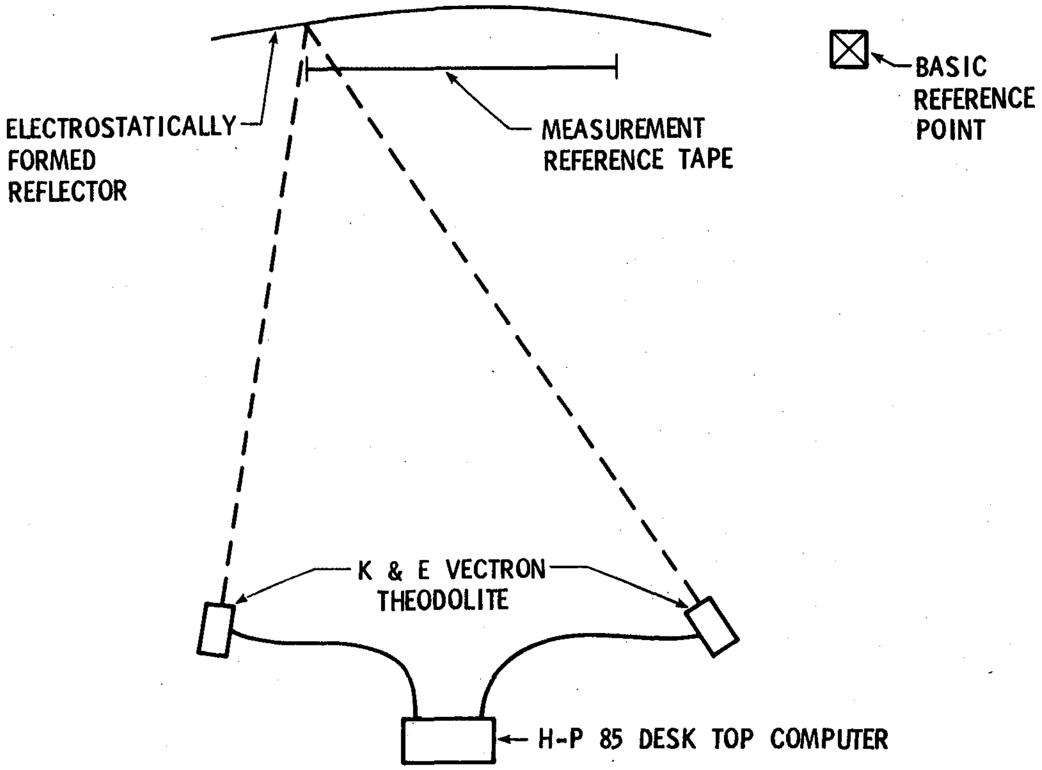


Figure 12. Schematic of Theodolite Measurement System.

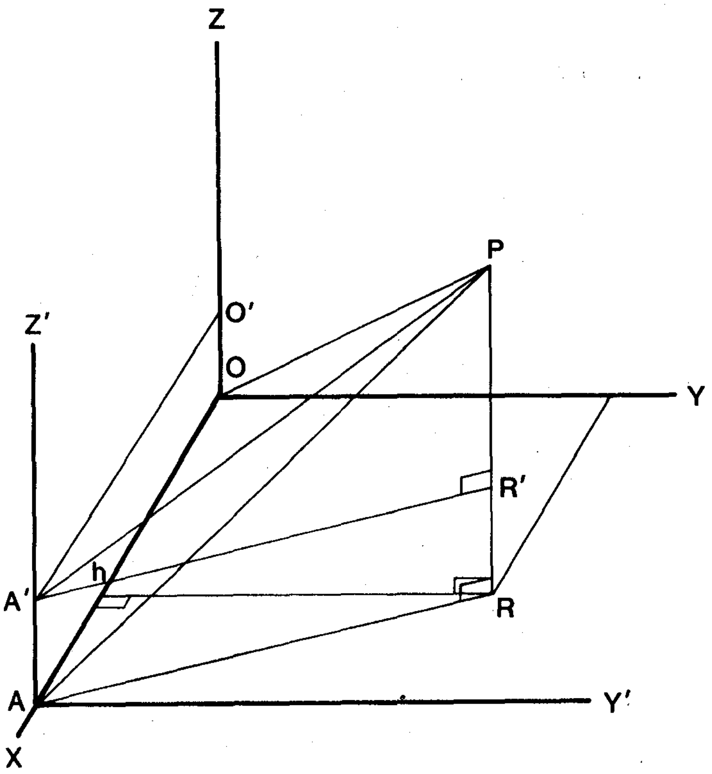


Figure 13. Triangulation Schematic for Derivation of Theodolite Measurement System.

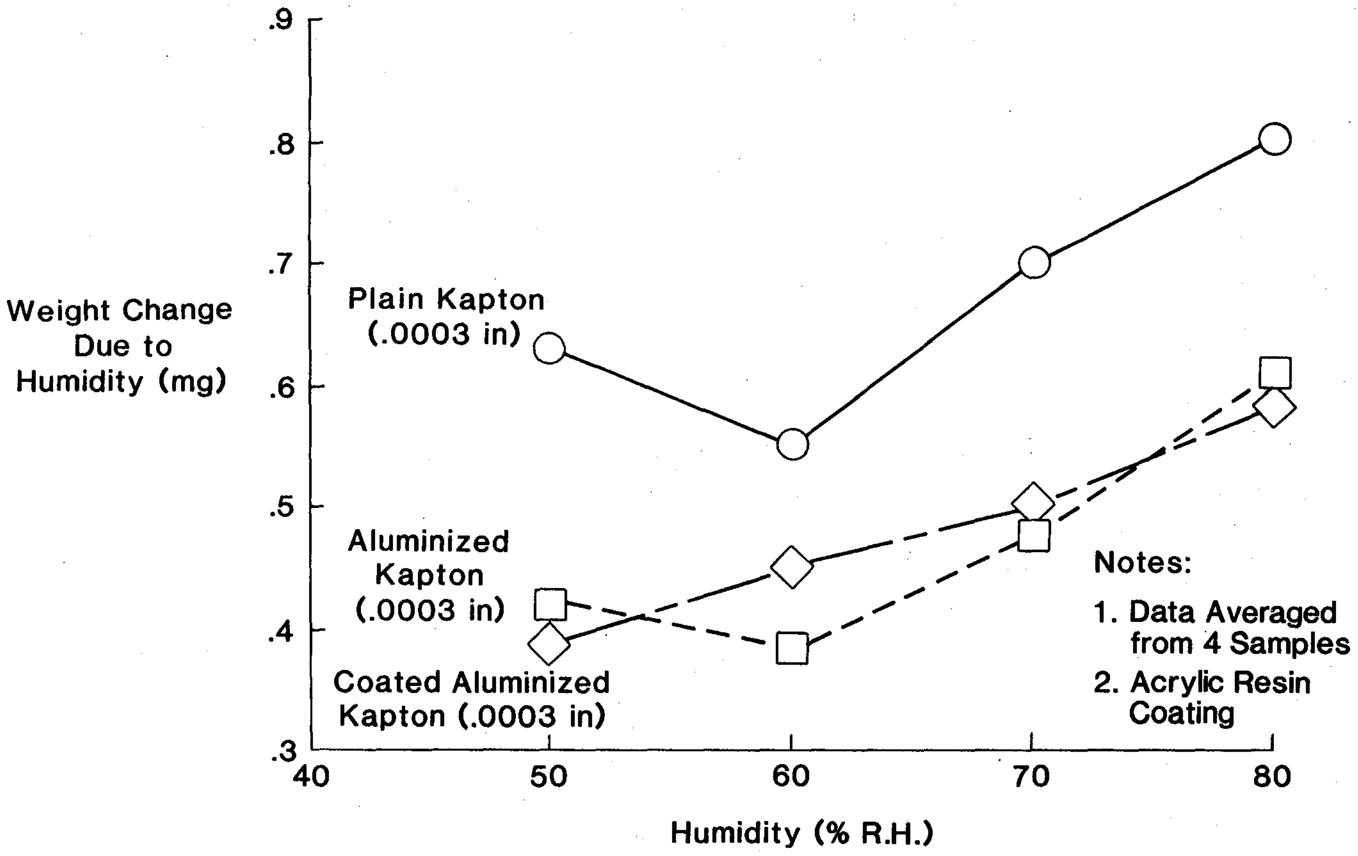


Figure 14. Comparison of Plain Kapton, Aluminized Kapton and Coated Aluminized Kapton When Exposed to Four Humidity Levels.

1. Report No.
NASA TM-86328

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Electrostatic Forming and Testing of Polymer Films
On a 16-Foot Diameter Test Fixture

5. Report Date
February 1985

6. Performing Organization Code
506-62-23-01

7. Author(s)
John W. Goslee, William F. Hinson, and William T. Davis

8. Performing Organization Report No.

9. Performing Organization Name and Address
NASA Langley Research Center
Hampton, Virginia 23665

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, DC 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The Large Space Systems Technology Program was instrumental in investigating different forms of large, lightweight, deployable structures which could be carried on the Space Shuttle. Different forms and concepts of antennas as a type of large space system were investigated. One of the concepts chosen to be evaluated was the electrostatically controlled membrane reflector made of metallized material. The concept appears to be a good candidate for creating an antenna with high surface quality and has the ability to be packaged and deployed from the Shuttle with a significant reduction in weight compared to other antenna types.

17. Key Words (Suggested by Author(s))
electrostatic, membrane, antenna
material forming

18. Distribution Statement
Unclassified - Unlimited

Subject Category 33

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
34

22. Price
A03

N-305

For sale by the National Technical Information Service, Springfield, Virginia 22161